Intermodulation Distortion in Linear Amplifiers

BY WILLIAM I. ORR,* W6SAI

Although there has been much talk about intermodulation distortion in linear amplifiers, a search of available literature brings to light very little in the way of factual data. Here's down-to-earth dope on what linear-amplifier tubes can and can't do.

It is common communication practice to generate a single-sideband signal at a low power level for reasons of economy and then to ampilfy it to the desired strength by the use of one or more linear amplifier stages. The intelligence is contained in amplitude variations in the signal, and it is imperative that the linear stages amplify this intelligence with as little distortion as possible. Strictly speaking, an ideal linear amplifier is one in which the output envelope amplitude is at all times directly proportional to the input envelope amplitude. Amplitude distortion results when the magnitude of the output signal is not strictly proportional to that of the driving signal. This class of distortion (which is the principal type encountered in linear amplifiers) includes *intermodulation distortion*, a particularly interesting type of amplitude distortion encountered in single-sideband service. In passing, it should be noted that intermodulation distortion (abbreviated IMD) occurs only in a nonlinear device driven by a complex signal having more than one frequency. As speech is made up of multiple tones (or frequencies) and as the perfect linear amplifier has yet to be built, the situation leading to IM distortion exists in most s.s.b. amplifiers. Once the intelligence-bearing signal has been generated, the amplitude relationships existing in the intelligence must be faithfully retained or the s.s.b. signal will blossom into a broad, fuzzy caricature of itself, and the unlucky user of the nonlinear equipment will find his on-the-air popularity waning. Intermodulation distortion, therefore, is important to the s.s.b. operator, and the cause and effect of this unloved and unwanted mutilation of s.s.b. signals will be discussed in this article.

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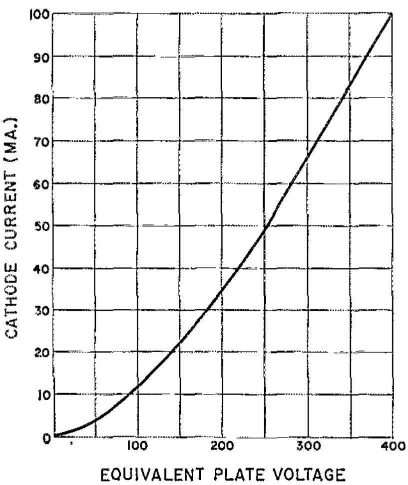

Fig. 1—The electron flow (cathode current) in a vacuum tube is a nonlinear function of the equivalent plate (or plate and screen) voltage and is described by the 3/2-power law. This curve illustrates typical electron flow, which plays an important part in establishment of tube linearity.

The Vacuum Tube and Linearity

The vacuum tube is the heart of the linear amplifier, and the amplifier is designed about it.[1] In addition to the tube, the amplifier is composed of auxiliary equipment — resistors, capacitors, inductors, etc. — chosen to permit the tube to operate in the most linear manner possible consistent with various restrictions imposed by economic, physical and electrical limitations. The auxiliary equipment may be considered to be made up of passive circuit elements while the vacuum tube is thought of as an active element by means of which the desired power gain is accomplished. The passive circuit elements are entirely linear and they affect circuit operation only insofar as they determine the operating parameters of the tube. The linearity of the tube is open to question. The more linear the tube, the less stringent the demand placed upon the circuitry to achieve a desired degree of over-all linearity. The results obtained are a balance between excellence and economy.

The vacuum tube utilizes electrons emitted from a hot cathode by impressing upon them an electric field which varies with time. During the passage of the electrons from cathode to plate, the field is manipulated in such a way as to alter the number of electrons arriving at the plate of the tube. The electric field reacts in a predictable way that may be accurately described by Maxwell's equations. The electron flow (or cathode current) is a 3/2 power function of the applied electrode voltages. This so-called "3/2-power

[1] This discussion applies to vacuum tubes. Similar conclusions may be drawn about transistors, but such conclusions are not within the scope of this article.

law" of Child and Langmuir is theoretically valid for uniform tube geometry and holds true for any space-charge-limited electron flow under the influence of an external field (Fig. 1). The 3/2-power law is not a linear function, and in practical tubes the cathode current is not a straight-line function of grid voltage. Further, practical tubes depart from the 3/2-power law to some extent, depending upon tube geometry, space charge, electron interception by grids, and emission limitations.

The relationship between the electric field and cathode-current flow within the tube described by this natural law plays an important role in the establishment of tube linearity. In practical amplifiers, for example, the magnitude relationship between input and output signals is not perfectly constant at all signal levels within a given range. The relationship defining *amplifier* linearity is termed the *envelope transfer function*, and ideal and typical transfer functions are shown in Fig. 2. The fundamental cause of a non-ideal, nonlinear amplifier transfer function may be traced directly to the nonlinear relationship between the plate current and grid voltage of the tube employed in the amplifier. This relationship *approximates* the 3/2-power law throughout the operating region above cutoff.[2] An examination of intermodulation distortion reveals the importance of significant cathode-current departure from this fundamental law as regards amplifier linearity.

Intermodulation Distortion Measurement Techniques

Leaving the vacuum tube for a moment, it is useful to examine means of testing tuned linear amplifiers for distortion. One such means is to apply two equal-amplitude r.f. signals of different frequency to the input circuit and then to measure the relative strengths of the output signals and the accompanying intermodulation products.[3] This combination of input signals is often called a *two-tone test signal*. The action of the test signals beating with each other in the typical "nonlinear" linear amplifier having amplitude distortion produces intermodulation distortion, and the purpose of the two-tone test is to create this action under controlled conditions and to measure it. Maximum limits of intermodulation distortion have become an important specifica-

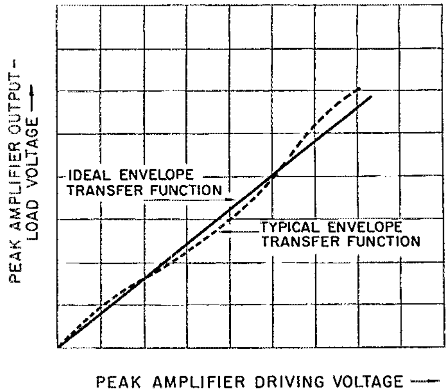

Fig. 2—Amplifier linearity is defined by the envelope transfer function. Departure from linearity is illustrated by curvature of the function (dotted curve) and may be traced directly to the nonlinear relationship between cathode current and electrode voltage shown in Fig. 1.

tion determining the excellence (or lack thereof) of linear amplifiers and tubes.

A practical test technique is to employ a two-tone, low-distortion test signal to drive a linear amplifier, and to use a spectrum analyzer to display a sample of the output signal of the amplifier (Fig. 3). A spectrum analyzer is a precision panoramic receiver having high resolution and capable of resolving signals separated in frequency by only a few kilocycles. The presentation of a portion of the spectrum in which the tests are taking place is given on a long-persistence cathode-ray tube. If the IMD products of the two-tone test signal are known and the amplifier under test is run with no feedback, at a frequency low enough to remove side effects due to circuit uncertainties, the IMD products of the tube under test may be readily determined by visual inspection of the picture on the screen of the spectrum analyzer. Equally important is the fact that the test is reproducible, and that the tube may be operated under any combination of electrode voltages and loads.

A block diagram of a typical IMD test experiment is shown in Fig. 4. The low-distortion signals are generated by separate stable r.f. oscillators operating on 2000 and 2002 kc., respectively, their outputs being carefully combined in a special isolator which prevents the oscillators

[2] Cutoff may be thought of as that amount of grid bias required to reduce the idling plate current of a vacuum tube to virtually zero.

[3] "The Grounded Grid Linear Amplifier," Orr, Rinaudo, Sutherland; *QST*, August, 1961, pages 16–21.

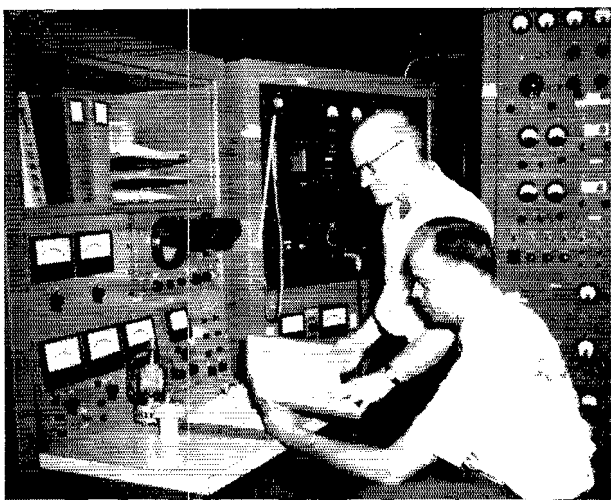

Fig. 3—QST authors and prominent DXers W6KEV (standing) and W6UOV examine data plotted by Eimac Intermodulation Distortion Analyzer. General-purpose equipment permits IMD measurements to be made on a wide variety of transmitting tubes in either grid- or cathode-driven configuration. IMD products are seen on screen of panoramic analyzer.

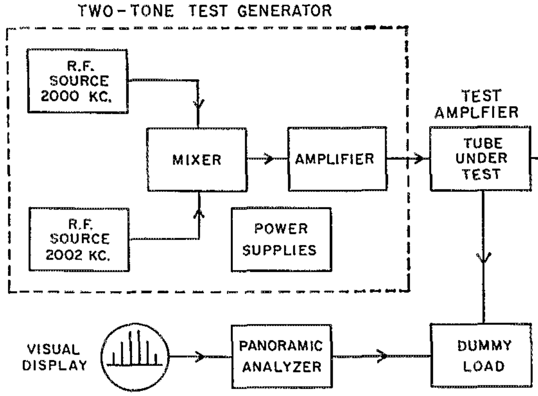

Fig. 4—Block diagram of Intermodulation Distortion Analyzer of Fig. 3. Low distortion two-tone r.f. signal is generated at 2 Mc. and applied to test amplifier. The output of the amplifier is dissipated in a dummy load and a portion of the output signal is examined on the screen of a high resolution panoramic analyzer. Distortion products as low as −60 decibels below peak power may be seen and studied.

from "seeing" each other. The resultant two-tone signal is amplified by successive class A stages until the desired driving level is reached. The two-tone generator shown in the photograph is capable of delivering a test signal having IMD products more than 60 decibels below the two-tone signals, at a power level up to 700 watts.

The tube under test is placed in a test amplifier operating at 2000 kc., and capable of permitting various electrode voltages and r.f. loads to be

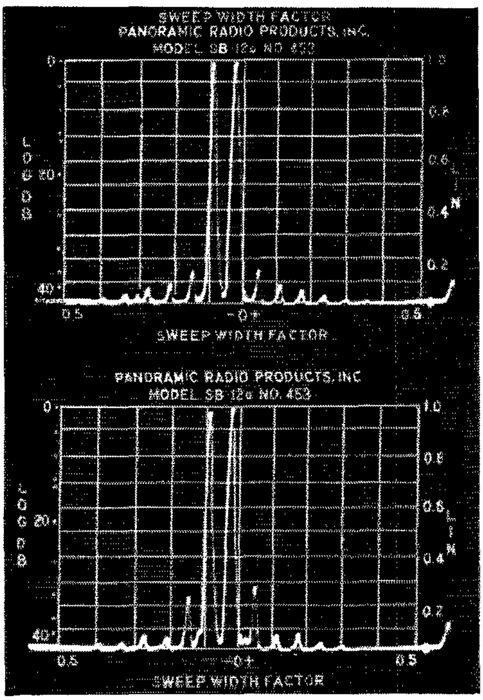

Fig. 5—Typical display on screen of IMD Analyzer. Top: Two test tones are seen at the center of the screen, with IMD products evenly displaced on either side of test signals. Third-order products are 35 db. down in amplitude from two-tone signal, and 5th-order products are 40 db. below test signals. Higher-order distortion products may also be seen. Bottom: Equipment parameters adjusted to raise third-order products and to drop fifth-order products. The linear amplifier may be adjusted to enhance or reduce various distortion products, if desired.

impressed upon the tube at the convenience of the operator. The output of the test amplifier is dissipated in a dummy load and a small portion of the output signal is applied to a panoramic analyzer having a dynamic range of 60 decibels. The two-tone test signal, along with spurious IM products, may be seen on the screen of the instrument, separated on the horizontal frequency axis by the difference in frequency between the two test signals (Fig. 5). A reading is made by comparing the amplitude of a specific intermodulation product with the amplitude of the two equal test tones in the output signal. For convenience, the ratio between *one* of the test signals and *one* of the IM products (there are always two of the same order) is read as a power ratio expressed in decibels below the test-signal level. It is equally correct, and the absolute answer is the same, if the ratio of the sum of the powers of the *two* test tones to the sum of the powers of the *two* IM products of the same order is used. It is equally valid to express IM relative to peak-envelope power, (p.e.p.) provided it is done by taking the ratio of p.e.p. to the square of the sum of the two IM products of the same order.[4] Referring IM to p.e.p. carries the additional information that the IM is specified for conditions of maximum signal level. Peak envelope power occurs when the two test tones are instantaneously in phase.

Measurements made on a wide variety of power tubes, from small to large, filamentary types and oxide cathode, triodes and tetrodes, in grid- and cathode-driven service, have shown conclusively that the magnitudes of the intermodulation distortion products are significantly affected by almost everything: changing heater or filament voltage by only a few per cent; slight shifts in bias voltage, idling current, screen voltage, plate or grid tuning; neutralization, loading — all these factors and others even more obscure enter into the determination of intermodulation distortion.

This might be a melancholy and discouraging picture, but it is a fact of life and is one of the

[4] Expressions of IM without reference to conditions of measurement and techniques are — as expressed by Poo-Bah in "The Mikado" — "merely corroborative detail, intended to give artistic verisimilitude to an otherwise bald and unconvincing narrative." Unfortunately, a trend seems to be developing in this direction. The reader is hereby warned.

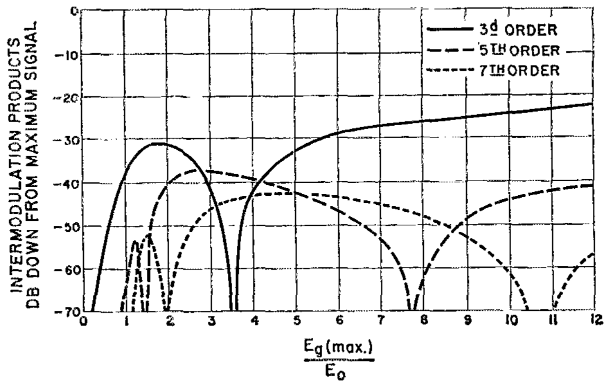

Fig. 6—Intermodulation distortion products may be predicted mathematically. This universal family of IMD curves applies to all perfect tubes obeying the 3/2-power law. The curves are plots of IMD level (Y axis) referred to the driving signal expressed as a ratio of drive to operating bias. As the drive is increased, the various IMD products pass through maxima and minima. Misleading conclusions of amplifier performance may be drawn if the equipment happens to be tested near a cusp on the IMD curve, where a particular product drops to an extremely low level. The whole operating range of the equipment must be examined to draw a true picture of IMD performance.

major roadblocks in joint industry efforts (working through the auspices of the Electronic Industries Association with the active cooperation of the U.S. Navy) to set up standards and testing procedures in order to establish a common yardstick for all to follow in vacuum tube IMD testing, rating and equipment design.

Mathematical Analysis

IMD products may be calculated by several methods.[5] The results of different valid mathematical techniques are in good agreement with each other, and also agree in general with data obtained from two-tone tests conducted with the IMD analyzer. A theoretical family of IMD curves of a perfect tube obeying the 3/2-power law is shown in Fig. 6. This universal family of curves applies to all tubes, regardless of operating parameters or tube type. Changes in electrode potentials and circuit values (and even changes in tube type) will produce characteristic curves of this general configuration, but of course the signal level at which particular value of distortion occurs will be different in each case.

In Fig. 6 intermodulation distortion products, expressed in decibels below the output level of the tube, are plotted along the Y axis. The ratio of the two-tone driving signal $E_{g(max)}$ to operating bias, E_o (relative to cutoff voltage) is plotted along the X axis. When E_o is zero, the tube is biased at cutoff (class B). Ratios of $E_{g(max)}/E_o$ greater than one, but less than infinity, represent the possible range of class AB operation. Starting on the curve at the no-signal point ($E_{g(max)} = 0$), the IMD products are nonexistent. As $E_{g(max)}$ is increased, the IM products increase throughout the range of class-A operation and into the class AB region, until a maximum IM distortion figure for the 3rd-order products of about -30.7 decibels is reached at an $E_{g(max)}/E_o$ ratio of about 1.7. The 3rd-order product then drops to zero (minus infinity) again for a ratio of $E_{g(max)}/E_o$, of about 3.5, after which the IM product again increases, gradually rising to a level near -20 decibels for class-B operation. Fifth-order and 7th-order (and higher-order) products follow this same general behavior, compressed along the X-axis, and are shown in dotted lines on the graph.

The results of this theoretical study imply that the amount of intermodulation distortion in any vacuum tube that follows the basic 3/2-power law is predictable; further, that such distortion is inescapable and is independent of tube type. Moreover, the study indicates that the perfect 3/2-power tube will provide 3rd-order IM products no better than -20 to -30 decibels below maximum power output, and that the IM product varies markedly with drive level, dropping to zero at various points in the dynamic operating range. Thus, the perfect tube, obeying a fundamental law of physics, is a mediocre performer from a linearity point of view. As far as IM distortion goes, it is a poor device to use in equipment

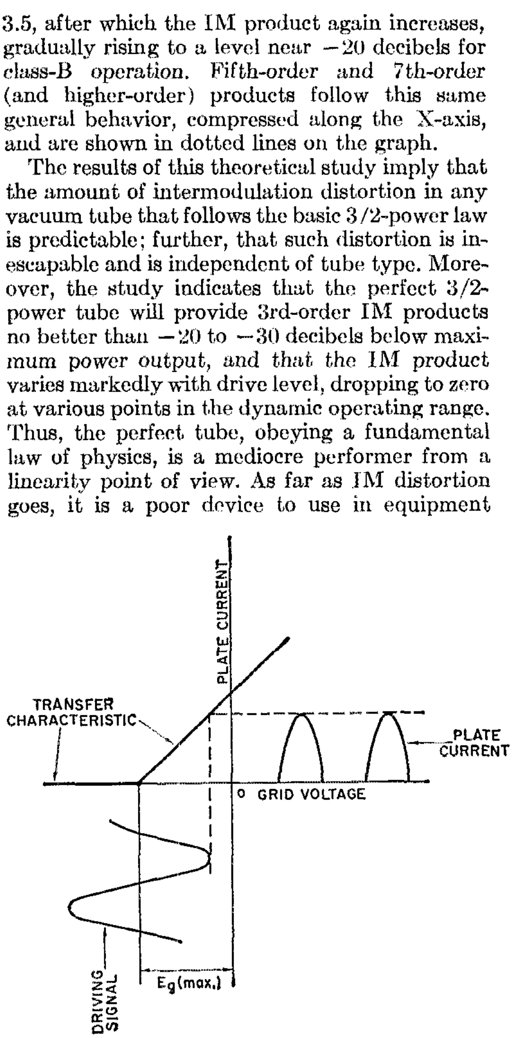

Fig. 7—An ideal tube transfer characteristic departs from the 3/2-power law. The ideal characteristic shown here consists of two linear portions, with the operating point set at the intersection. Half-wave plate current pulses are converted to sine waves by the flywheel effect of the plate tank circuit. Poor tank circuit Q, therefore, will have adverse effect on over-all linearity.

[5] "Approximate Intermodulation Distortion Analyses." Report CTR-173 by R. E. Cleary, Collins Radio Co., Cedar Rapids, Iowa; "Linear Power Amplifier Design," W. B. Bruene, *Electronics*, August, 1955; "Linearity Testing Techniques for SSB Equipment," Icenbice and Tellhaver *Proc. I.R.E.*, December, 1956, pages 1775–1782. "Intermodulation Distortion in High Powered Tuned Amplifiers," R. C. Cummings, Consultant, Eitel-McCullough, Inc., San Carlos, California.

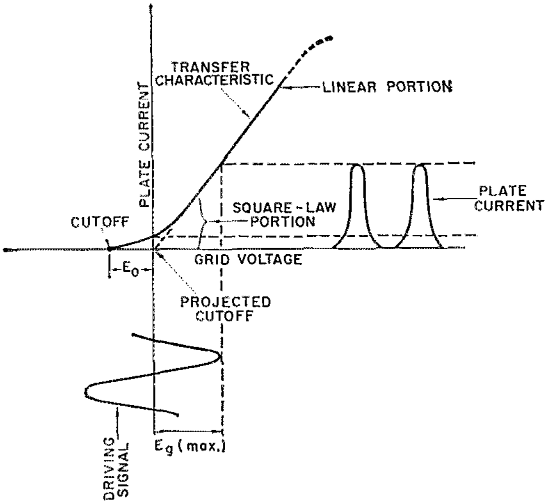

Fig. 8—Another ideal transfer characteristic for a linear tube consists of this form of curve, where the central portion is straight and the lower portion resembles a parabola. Practical tubes exhibit transfer characteristics of this general class, the upper portion of the curve showing additional curvature resulting from saturation of the electron stream in the grid-plate area of the tube. Plate current pulses are converted to sine waves by flywheel action of plate tank circuit.

designed for linear amplification of intelligence-bearing signals.

A Study of Practical Linear Amplifier Tubes

Does this theoretical study actually mean that all tubes are poor linear amplifiers or that it is impossible to achieve IM distortion products of a better order than −20 decibels? Not at all. The study concerns itself with a *perfect* tube that implicitly follows the 3/2-power law. Of course, there is no such device, and *practical* tubes (i.e.: tubes that can be manufactured) depart from this law to a greater or lesser extent. The practical tube, in general, shows an improvement in over-all linearity as a result of departure from the 3/2-power law. The practical tube, in addition, does not have a definite value of cutoff grid voltage, it does not have constant amplification at all points within the structure, and current deviations and amplification variations occur with changes in plate voltage. Current intercepted by the screen and control grids modifies the plate characteristic, and the "constants" that express the 3/2-power law vary with actual operating conditions. Theoretically, IM distortion as a result of this law should be independent of tube type. We know from experimental data that such is really not the case, as practical tubes exhibit transfer characteristics departing markedly from the 3/2-power law. In many instances, an improvement in linearity occurs when the tube departs from this law. For example, an ideal transfer characteristic for a tuned amplifier is shown in Fig. 7, consisting of two linear portions with the operating point set at the intersection. The resulting plate current consists of rectified and amplified half sine waves, the plate tank circuit converting this misshapen wave into an equivalent sine wave by virtue of the fly-wheel effect. The equivalent sine wave is directly proportional to the input signal at all amplitude levels from zero to the maximum value shown.

Alternatively, distortionless linear amplification may be achieved from another transfer characteristic having, instead of the discontinuity exhibited in the first example, a smooth curve of the form shown in Fig. 8. The operating point of the tube is chosen at projected cutoff. Ideally, the curved portion of the transfer characteristic should be a portion of a so-called "second-order" curve (a half-parabola, to be exact). A characteristic such as this is termed *square law*. Distortion products added to the exciting signal by such a

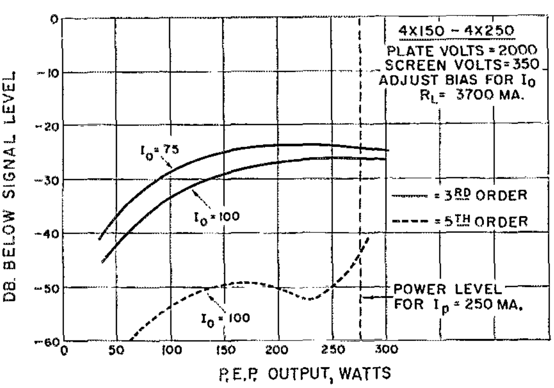

Fig. 9—A family of IMD curves for the 4X150–4X250 external-anode tubes. These curves are representative of this type of tube, and are typical for tubes made by different manufacturers. Intermodulation distortion products average about −25 decibels below peak signal, for 3rd-order products, while 5th-order products average −43 decibels below peak signal. These curves are representative of most small transmitting tubes of this type. Changes in loading or circuit parameters will alter shape and position of the curves.

curvature can be filtered out of the output signal by the tuned plate tank circuit *because all of these products fall in the harmonic regions of the exciting signal.* A distortionless replica of the input signal is thus available at the output circuit of the amplifier. Other transfer characteristics exist which also will provide lower-distortion output. Practical tubes departing from the 3/2-power law (wherein the exponent in the expression is 3/2, or — expressed as a decimal — 1.5) have exponents ranging from 1.3 to 3.4. This range covers quite a spectrum of possible tube performance! A practical tube may have a transfer-characteristic exponent falling somewhere between 1.5 (3/2-power law) and 2 (square law); its transfer characteristic would approximate the curve of Fig. 8, wherein the central portion is fairly linear and the lower portion resembles a parabola. The upper portion of the characteristic may show additional curvature resulting from saturation of the electron stream in the grid-plate area of the tube. That is to say, the grid or screen "robs" the plate of the greater portion of the available electrons and causes a corresponding drop in plate current.

Intermodulation tests run on tubes having this general transfer characteristic show distortion products generally in agreement with the 3/2-power law. Shown in Fig. 9 are IM curves based upon typical measurements made on the 4X150 - 4CX250 family of external-anode tubes. With fixed values of plate and screen potential and plate load impedance, measurements were made at two levels of resting plate current over the operating range of the tube. At the recommended value of resting plate current, the 3rd-order IM products rise gradually and smoothly as power is increased to the maximum value of 500 watts (referred to a single-tone plate current of 250 ma.) until at this value the products reach a level of −26 db. below the p.e.p. signal. Decreasing the resting plate current to 75 ma. will degrade the IM curve by several decibels, as shown. Fifth-order products at the recommended value of plate current are below −43 db. at maximum plate current level. The addition of 10 decibels of negative feedback to a circuit employing this style of tube will reduce the IM products below the values shown by approximately 10 db., so

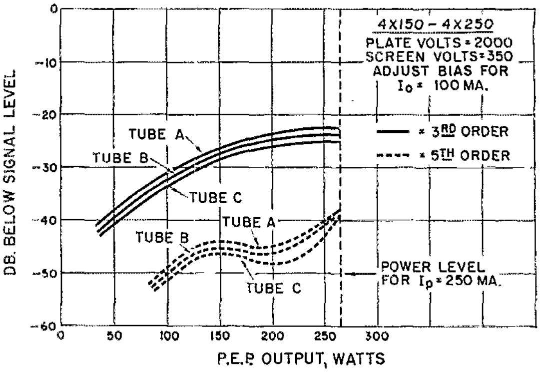

Fig. 10—Intermodulation distortion products vary from tube to tube of the same type, and also vary tube to tube as operating conditions are changed. Small "receiving-type" transmitting tubes are usually poorer than these curves by five to ten decibels.

equipment with feedback designed around this tube (other factors being equal) should be able to reach the region of −35 db. IM distortion at full power. Individual tubes (and similar tubes made by different manufacturers) will vary from these curves by two to three decibels. Fig. 10 shows the variation in IM products between three tubes under fixed operating conditions. Changes in loading or other parameters will alter the shape and position of these curves.

Referring back to Fig. 6, tubes of this type are operated under conditions corresponding to a ratio of $E_{g(max)}/E_o$ in the range of 2 to 3 at maximum signal, and therefore distortion must pass through the third-order product maximum of about −31 db. within the operating range. Actually, maximum distortion appears near the 70% to 100% power level and is of the order of −25 db. or so. These curves are quite representative of most power tubes employed in amateur equipment, common varieties of transmitting tubes falling in the "minus twenty" to "minus thirty" decibel intermodulation range. Judicious use of feedback with these tubes will allow IM distortion products to fall in the "minus thirty" to "minus forty" decibel range.

Recent tubes specifically designed for linear

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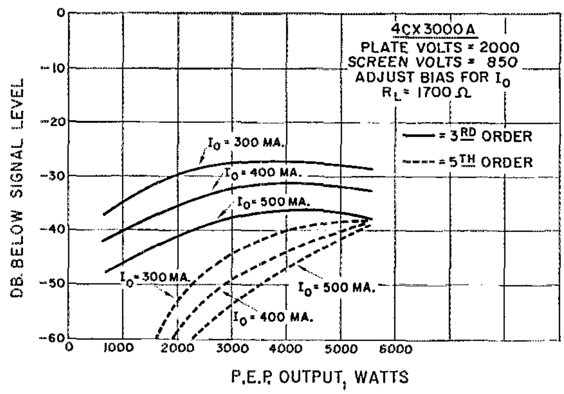

Fig. 11—Eimac 4CX3000A, specifically designed for linear-amplifier service shows substantially better IMD products by virtue of departure from 3/2-power law. With resting plate current of 500 ma., 3rd- order products are down better than 35 db. from peak signal level.

c.w. crop is choice, too, led by AC4NC, C3BF, CRs 5AA 1ØAB, FKS8AA, FU8AC, HE9LAA, KAØIJ, MF2AG, MI3LK, OQ5GU, TA3AA, UG6KAA, VK1BA, VSs 2CP 2DF 7MC, YI2AM, ZCs 3AC 6OR, 9S4s AZ and BS —...— Forty c.w. is fine for FK8AN, KW6BB, OQØDZ, UI8KAA, VS2CC, W5TUX/KJ6 and YA3FOV, while 7-Mc. phone followers mention DU9BL, KW6BI and PJ2CE —...— Fifteen phone turns up CR4AI, EA9AR, YI3WH and ZD9AA. Code merchants on 21 Mc., including a few ambitious Novices, deal with FF8AG, TA2EFA and VU2ET —...— Some odds and ends: HS1WR is all set to work Ws when the ban is lifted there. . . . ZL3JA threatens Tokelaus DX developments. . . . W7PGX (c.w.) and W6DI (phone) top U.S.A. scorers in the 1952 VK/ZL Test. VE7AIH led Canada in both categories. . . . East German DMs are said to be ready for action. . . . W9s KA and NN work up a W9-DXCC get-together. . . . CEØAA (CE3AG) pulled off a huge Easter Island DX contest in mid-August. QST

The Moonbounce Problem

(*Continued from page 22*)

These figures show, among other things, that the initial 1296-Mc. moonbounce, with an 18-foot dish (35 db.) and 300 watts of transmitter power, was both a technical triumph and an operating feat. It is also clear that the higher frequencies are the logical choice for both commercial and amateur work of this type.

As Soifer[7] recently noted, the basic problem is to obtain adequate signal-to-noise ratio, and the graphs presented here should help the equipment- and antenna-oriented amateur get a feel for the moonbounce problem. It should be remembered, however, that marginal systems give marginal results (if any at all), and that these numbers should be used conservatively if reliable communication is the goal. QST

[7] Soifer, "Space Communication and the Amateur" *QST*, November, 1961.

Intermodulation Distortion

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amplifier service show a decided improvement in IM distortion figures. Fig. 11 shows typical IM values for the 4CX3000A. Depending upon the value of resting plate current, the 4CX3000A is capable of delivering a p.e.p. output of 5.5 kilowatts with 3rd intermodulation products as low as −36 db. or more below the signal level. With the addition of ten or fifteen decibels of feedback, the construction of a high-power, high-quality linear amplifier having IM products in the region of −50 db. below the signal level becomes a reality.

Conclusion

The idealized vacuum tube is a 3/2-power-law device, and theoretically is incapable of low intermodulation distortion, except for low-efficiency class-A operation. By careful design of tube parameters aimed to remove the tube from this style

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of operation, a considerable improvement in linearity is possible. Even so, the circuit designer must follow the tube manufacturer's recommended operating conditions closely (voltages, loading, etc.) to achieve optimum performance, as these recommendations are usually based on exhaustive tests. Most of us, unfortunately, simply do not have comparable test setups to allow us to know what improvement or (more likely!) degradation will take place when operating conditions begin to wander, or when a desire to "push the tube to the limit" overcomes common sense.

As the state of the art advances, more and better tubes — designed for linear amplifier service — will appear on the market, making the equipment manufacturer's job an easier one, and helping the equipment operator to have a high-quality, low-distortion signal on the air. QST

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Correspondence From Members

(Continued from page 85)

proving operating conditions and weeding out those individuals who either cannot, or will not, distinguish the woods from the trees. — *Johnson County (Kansas) Radio Amateur's Club.*

. . . Those howling about the added effort needed to gain the higher class are all too content to join that sliding group of amateurs. If we maintain the present trend of licenses we will be another CB band . . . — *WA2DJJ.*

Without the League ham radio wouldn't be the same. I am in favor of incentive licensing. I received my General license at age 13 (two years ago) and truly believe that anyone who tried could meet further qualifications. — *WA4BSE.*

Technical Correspondence

(Continued from page 75)

frequencies, and at least some rejection of signals outside the ham bands. With both of the schemes mentioned above, the level of the nonamateur signals at the receiver input is increased as well as the amateur band signals. This can result in problems in two areas: reduced image rejection (due to the use of components which amplify rather than reject the image frequency), and increased susceptibility of the receiver to overloading from strong nonamateur signals.

Another problem which could arise due to the broadband characteristics of the log-periodic antenna is that of efficient radiation of undesired transmitter outputs. These outputs might be undesired multiplication products in the usual a.m./c.w. v.h.f. transmitter, or undesired heterodyne products with v.h.f. s.s.b. rigs. In either case, the antenna would give excellent gain rather than attenuation (as would be the case with a Yagi-Uda antenna) at some of the frequencies at which undesired outputs occur. This obviously increases the

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